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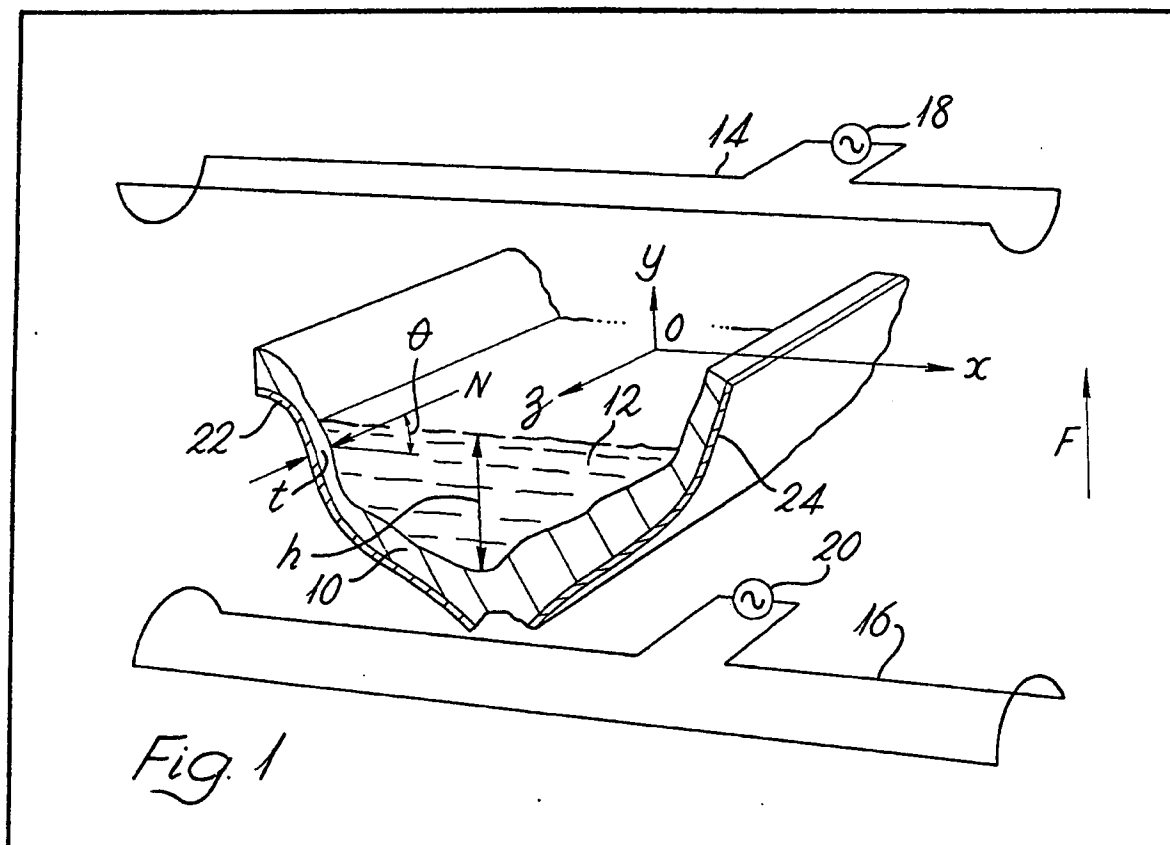
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(54) Electromagnetic Channel  
Flowmeter

(57) A flowmeter for measuring the flowrate of a liquid 12 of moderate electrical conductivity, such as water, along a uniform duct 10 in which the liquid 12 has a free surface comprises an electrode 22, 24 on either side of the duct; means for applying a magnetic field  $F$  (e.g. by coils 14, 16) which has at least a component in the vertical direction ( $y$ ) and which is

invariant along the axis ( $x$ ) between the electrodes 22, 24; and potential sensing means for sensing the electrical potential generated between the electrodes by flow of the fluid. The arrangement is such that a virtual current between the electrodes would be horizontal with no vertical component. The electrodes 22, 24 extend at least to the top and to the bottom of liquid 12 and may each comprise a spaced array of electrodes. A shorting resistor may be connected between the electrodes and the voltage across the resistor measured. The duct may be formed of a thin electrically resistive material of such thickness at any point that the electrical admittance per unit area is proportional to the cosine of the angle  $\theta$  in the vertical plane between the normal to the internal wall of the duct and the horizontal.



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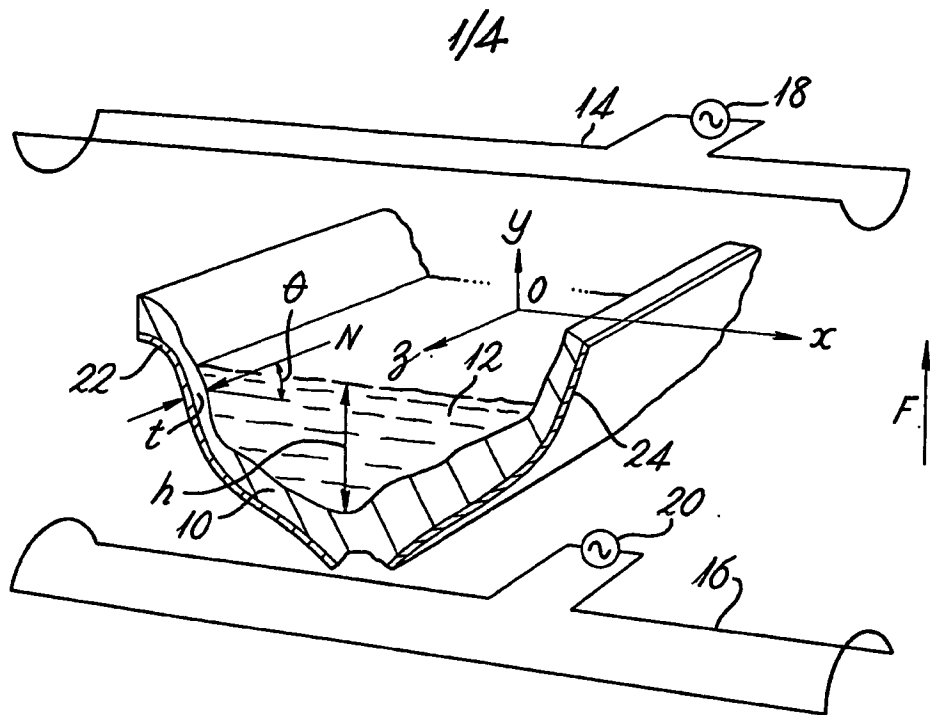


Fig. 1

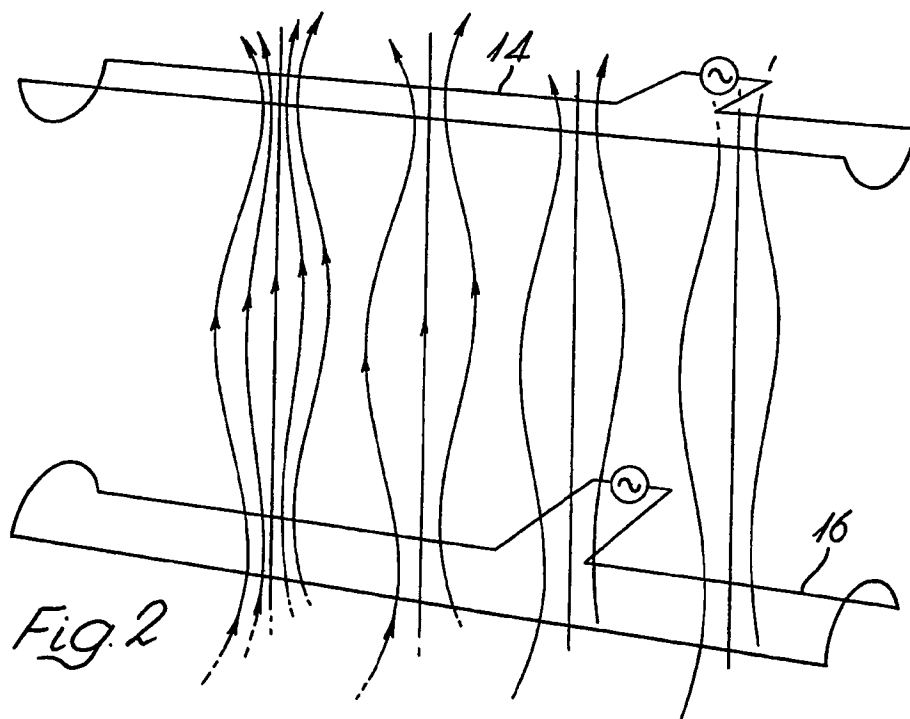


Fig. 2

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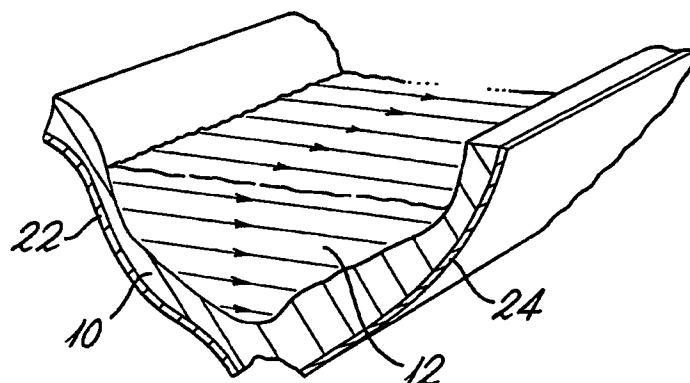


Fig. 3

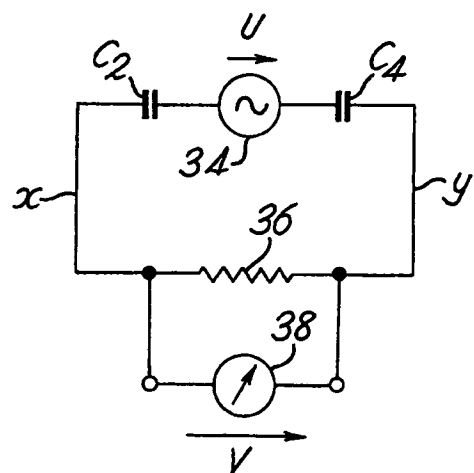


Fig. 4

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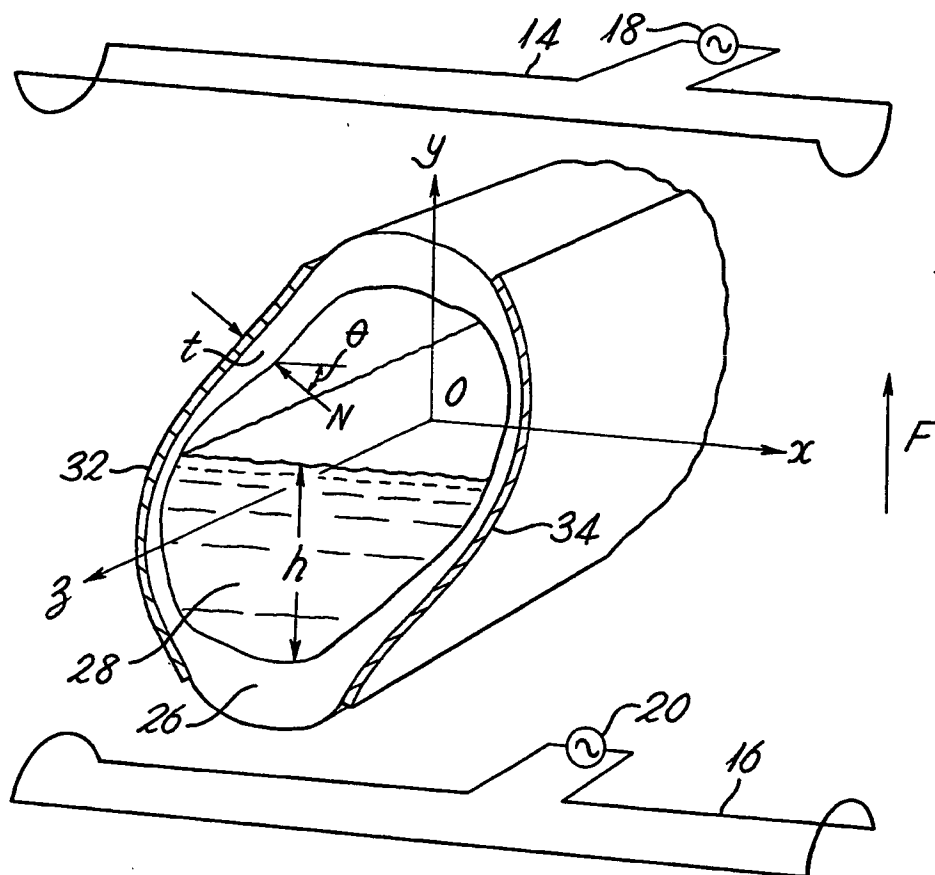


Fig. 5

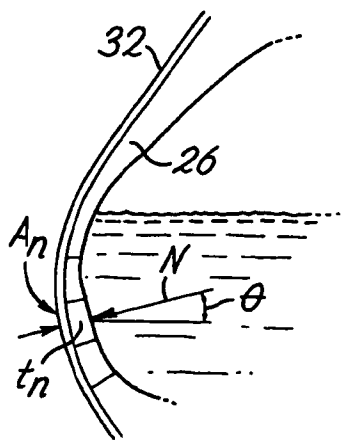


Fig. 6

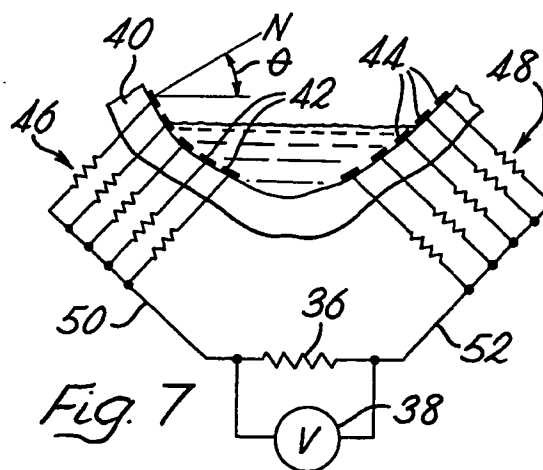
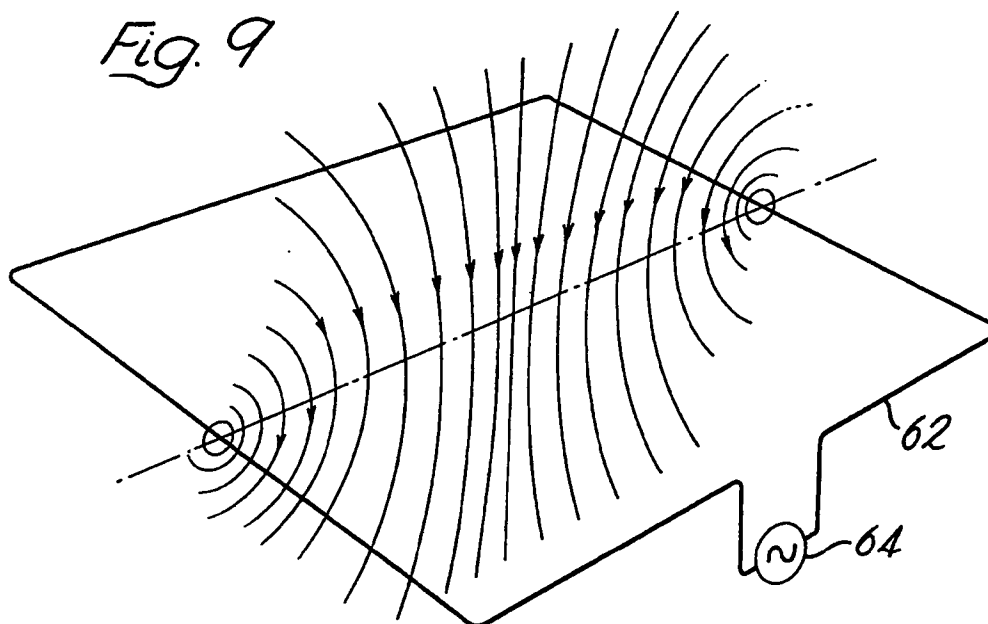
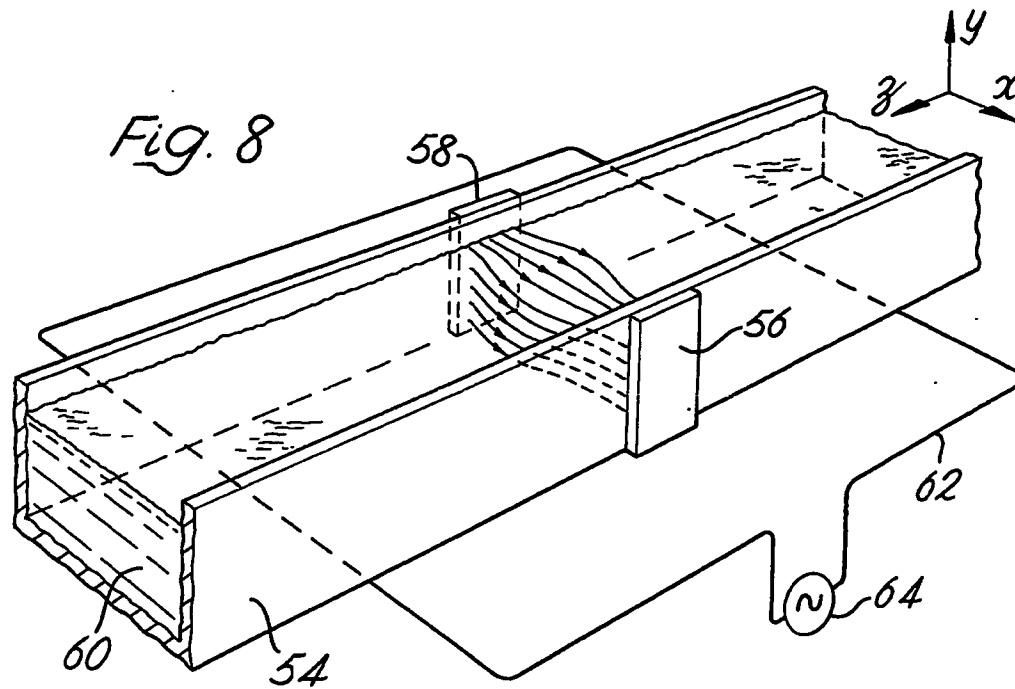


Fig. 7

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# **SPECIFICATION** **Channel Flowmeter**

This invention relates to the measurement of flow of a liquid which is a moderate electrical conductor, (that is, having a conductivity in the range  $10^{-5}$  to  $10^5$  Mhos/metre) such as water, in an open channel or partly filled pipe.

In an electromagnetic flowmeter a magnetic field is applied across a duct containing a flowing fluid normal to the direction of flow. The potential generated in the liquid by virtue of its movement through the magnetic field is sensed by electrodes on opposite sides of the duct. For diametrically opposed point electrodes applied to a circular duct the potential generated is proportional to the mean velocity in the duct provided the magnetic field is uniform and the velocity profile of the liquid in the duct is axisymmetric. In practice, the velocity profile may not be axisymmetric and errors arise.

In UK patent application No. 801 1624, a method and apparatus are described with allow compensation of the errors and the accurate measurement of flowrate of a moderately conducting liquid flowing through and filling a closed pipe. In the present invention, similarly accurate methods of measurement are applied in the more complex case of flow along a duct such as an open channel or a partially filled pipe, when the liquid will have a free surface.

In this specification it will be assumed for clarity that the duct and the free surface of the liquid are horizontal. It is also possible to apply the invention when the duct is tilted so that the liquid flows down it under gravity, so long as the free surface remains substantially plane and substantially parallel to the longitudinal axis of the duct.

According to the invention, a flowmeter for measuring the flowrate of a liquid of moderate electrical conductivity comprises a duct of uniform cross section along which the liquid flows and in which the liquid has a horizontal free surface; two electrodes arranged one on either side of a vertical plane along the direction of flow and extending at least to the top and to the bottom of the liquid; means for applying a magnetic field to the fluid in the duct, the magnetic field having at least a component in the vertical direction and being invariant in the horizontal direction perpendicular to the liquid flow and between the electrodes; and potential sensing means for sensing the electrical potential between the electrodes caused by flow of the fluid; the arrangement being such that a virtual current between the electrodes would be horizontal and have no vertical component.

In one embodiment, the flowmeter is arranged so that between the liquid and each side of the sensing means there is an electrical admittance per unit area of the duct wall which is proportional to the cosine of the angle in the vertical plane between the normal to the internal wall of the duct and the horizontal, in which the length of the electrodes in the direction of flow is at least twice the maximum width of the liquid free surface, and in which the magnetic field is relatively narrow in the direction of flow, whereby a horizontal and one-dimensional virtual current would flow perpendicular to the liquid flow.

In an alternative embodiment, the flowmeter is such that between the liquid and each side of the sensing means there is an electrical admittance per unit area of the duct wall proportional to the normal component of any horizontal and two-dimensional virtual current field which is generally transverse to the liquid flow and relatively short in the axial direction, and the magnetic field is uniform over a length of the duct which is at least twice the maximum width of the liquid free surface, whereby a horizontal and two-dimensional virtual current would flow generally transverse to the liquid flow.

In the two alternative embodiments, the length of the electrodes and the length over which the magnetic field is uniform respectively in comparison with the maximum width of the free surface of the liquid are such that the measurements can be made to a reasonable degree of accuracy. To increase the accuracy, the respective lengths must be increased.

Also according to the invention, a method of measuring the flowrate of a liquid of moderate electrical conductivity comprising causing the liquid to flow along a duct of uniform cross section and in which the liquid has a horizontal free surface; applying to the fluid in the duct a magnetic field which has at least a component in the vertical direction and which is invariant in the horizontal direction perpendicular to the liquid flow; and sensing any electrical potential generated between two electrodes arranged one on either side of a vertical plane along the direction of flow and extending at least to the top and to the bottom of the liquid, the arrangement being such that a virtual current between the electrodes would be horizontal and have no vertical component.

The invention will now be described by way of example only with reference to the accompanying drawings in which:—

Figure 1 shows part of an open channel through which liquid flowrate is to be measured;

Figure 2 illustrates the magnetic field in the region of the channel shown in Figure 1;

Figure 3 illustrates the virtual current which would flow in the liquid in the open channel;

Figure 4 is a schematic representation of a flowmeter according to the invention;

Figure 5 shows part of a pipe partly filled with liquid, the flowrate of which is to be measured;

Figure 6 is a section through a part of a channel wall showing elemental capacitors;

Figure 7 shows a major alternative arrangement which can produce the electrical admittances required in a flowmeter according to the invention;

Figure 8 shows part of an alternative form of a device for measuring liquid flowrate along an open channel and illustrates the virtual current; and

Figure 9 illustrates the magnetic field in the Figure 8 arrangement.

In Figure 1, a generally V-shaped channel 10 of insulating material contains a moderately  
5 conducting liquid 12, such as water. The liquid 12 flows along the channel and has a horizontal free surface. The longitudinal axis, i.e. the direction of flow, will be referred to as the  $z$  axis, the other horizontal axis as the  $x$  axis, and the vertical direction as the  $y$  axis. The channel is uniform in the  $z$  direction both internally and externally.

Above and below the channel are two magnetic coils 14, 16, each consisting essentially of two  
10 long, closely spaced wires, extending in the  $x$  direction, and each connected to a source 18, 20 of alternating current. When current flows in the coils a vertical magnetic field is generated, as indicated by the arrow  $F$ . The magnetic field lines are illustrated in Figure 2; between the centres of the two narrow coils the field lines are straight and vertical, while towards the outside of each narrow coil, the field lines diverge then converge. The field is unchanging along the  $x$  axis and this is the critical feature  
15 in the flowmeter.

Referring once more to Figure 1, on the outside of the channel are two electrodes 22, 24, extending along the channel in the  $z$  direction sufficiently far to avoid end-effects and extending above and below the liquid 12 in the channel.

When the moderately-conducting liquid flows along the channel and through the magnetic field,  
20 a potential difference is generated between the electrodes depending on the flowrate. The capacitance between the electrodes varies with the height  $h$  of the liquid above the bottom of the channel, and in most practical situations  $h$  will be unknown. In the flowmeter according to the invention, the arrangement is such that capacitance is directly proportional to the height  $h$ , and the potential difference generated is proportional to the flowrate divided by the height  $h$  independently of the  
25 velocity distribution.

This is achieved by arranging the thickness  $t$  of the channel walls at any point to be inversely proportional to the cosine of the angle  $\theta$  in the  $x$ - $y$  plane between the normal  $N$  at that point and the horizontal i.e.

$$t = \frac{k_1}{\cos \theta} \quad (1)$$

30 where  $k_1$  is a constant. When the channel walls are of homogeneous material, there is equivalent to the electrical admittance per unit area being proportional to  $\cos \theta$ .

This choice of wall thickness is such that the virtual current, i.e. the current which would be set up in the liquid 12 if a unit alternating current was passed into electrode 22 and extracted from electrode 24, is uniform and in the  $x$  direction (except near the ends of the electrodes) for any height  $h$  of liquid.

35 The direction of current flow is illustrated in Figure 3. The current density would be constant throughout both the depth of the liquid and between the electrodes in the part of the channel between the magnetic coils 14, 16, although actual values depend on the depth of liquid  $h$ , the virtual current being proportional to  $1/h$ . Towards the ends of the electrodes at positions remote from the magnetic coils the current flow is greatly distorted due to electrode end effects, but most of the current passes  
40 directly between the electrodes and at the electrode ends the magnetic field is weak.

In practice, of course, the actual current flow is movement of the moderately conducting liquid along the duct and through the magnetic field. It is known that the open circuit inter-electrode potential  $U$  generated by liquid motion is given by:—

$$U = \int \underline{B} \times \underline{j} \cdot \underline{v} \, d\tau$$

45 where  $B$ ,  $j$  and  $v$  and  $d\tau$  are respectively magnetic induction, virtual current, liquid velocity, and an element of volume of the liquid.

In theory the arrangement is ideal, i.e. it is insensitive to velocity distribution. Therefore:—

$$\underline{B} \times \underline{j} = \nabla \phi$$

where  $\phi$  is a scalar (see Journal of Fluid Mechanics, 43, 1970, page 577, in an article by M. K. Bevir).

50 Also

$$U = \int \nabla \phi \cdot \underline{v} \, d\tau = \int \phi \underline{v} \cdot d\underline{s} = (\phi_1 - \phi_2) Q$$

where  $\phi_1$  and  $\phi_2$  are the values of  $\phi$  for  $Z = \pm \infty$ .

Now

$$\phi_1 - \phi_2 = \int_{-\infty}^{+\infty} (\underline{B} \times \underline{j})_z \, dz$$

Since  $j$  is proportional to  $1/h$ , then  $\phi_1 - \phi_2$  is also proportional to  $1/h$  and so:—

$$U = \frac{k_2 Q}{h} \quad (2)$$

where  $k_2$  is a constant.

It is possible to measure  $U$  and the capacitance  $C$  between the electrodes independently and simultaneously and obtain the flowrate by automatic multiplication of the two.

Alternatively it is possible to eliminate  $h$  in equation (2) by measuring not  $U$  but the voltage  $V$  across a shorting resistor. This is illustrated in Figure 4 in which the open circuit potential difference generated by virtue of the liquid flowing through a magnetic field is indicated schematically, reference 34, and the capacitances between the liquid and the electrodes 22, 24 in Figure 1 are represented by  $C_2, C_4$ . The sides of the capacitances remote from the liquid are connected to opposite ends of a shorting resistor 36 of value  $R < 1/\omega C_2$  (where  $\omega$  is the working frequency and  $C_2 = C_4$ ).

The current  $i$  is accordingly

$$i = \frac{U}{\frac{1}{2j\omega C_2}}$$

thus

$$V = iR = \frac{1}{2}j\omega RC_2 U \quad (3)$$

The choice of wall thickness in accordance with equation (1) ensures that  $C_2$  and  $C_4$  are proportional to  $h$ , thus by (2) and (3),  $V$  is proportional to  $Q$  and is independent of  $h$ .

The voltage generated across the resistor 36 is measured by a voltmeter 38, and the reading is proportional to flowrate independently of height  $h$  and velocity distribution. This is a practical advantage of great importance, allowing accurate measurement of the flowrate of a moderately conducting liquid under widely varying practical conditions.

An alternative arrangement to Figure 1 is shown in Figure 5. Magnetic coils 14, 16 are provided above and below a closed pipe 26 of insulating material partially filled with a liquid 28 having a horizontal free surface. Two electrodes 32, 34 are arranged on either side of the pipe and in contact with it, extending above and below the liquid 28 and separated by longitudinal gaps at the top and bottom of the pipe.

The thickness of the pipe walls is chosen in accordance with equation (1) as in the Figure 1 embodiment.

Referring now to Figure 6, it will be demonstrated that  $C$  is proportional to  $h$ . Consider a part of the wall of the pipe 26 with electrode 32 and consider that the total capacitance is made up of a number of small plate capacitors of length  $L$  in the  $z$  direction and  $dl_n$  in the circumferential direction, corresponding to the element of height  $dh_n$ .

The area of each electrode  $A_n$  is given by

$$A_n = L dl_n \quad (4)$$

and

$$dl_n \cos \theta = dh \quad (5)$$

From equations (1), (4) and (5) it follows that

$$C = \sum_n \frac{\epsilon L dl_n}{k_1} \cos \theta = \frac{\epsilon L}{k_1} \sum_n dh = \frac{\epsilon L h}{k_1}$$

where  $\epsilon$  is the permittivity of the wall material. It can be seen that  $C$  is proportional to  $h$ .

A major alternative arrangement is possible in which electrical admittance per unit area is proportional to  $\cos \theta$ . This is illustrated schematically in Figure 7. A generally V-shaped channel 40 of insulating material has on its inner surfaces two arrays 42, 44 of small area electrodes each connected to one resistor in resistor networks 46, 48. The figure shows only the electrodes at one transverse section of the channel; each electrode array will cover an area of the channel walls in a two-dimensional array and only part of the resistor network is illustrated.

The ends of the resistor network remote from the electrodes are connected through common rails 50, 52 to opposite ends of the shorting resistor 36 across which the voltmeter 38 is connected.



The values of the resistors in the network are chosen in accordance with the area associated with each electrode and the orientation of the channel wall to which the electrodes are attached so that electrical admittance per unit area is proportional to  $\cos \theta$ , as in Figures 1 and 5.

In the Figure 1 and 5 embodiments, if it is impractical to alter the thickness of the duct wall, the required thickness can be achieved by the provision of packing material between the walls and the electrodes. 5

Typical dimensions for the magnetic coils 14, 16 and the electrodes 22, 24 and 32, 34 are that the long sides of the magnetic coils are also the lengths of the electrodes should be at least twice the maximum width of the channel 10 or the diameter of the pipe 26. The short sides of the magnetic coils are not critical so long as a magnetic field is generated and are typically of length equal to half the channel width. In any arrangement, the longer the electrodes, the smaller the distortion due to end effects and the higher the accuracy of the measurement. 10

It is also possible to use only one magnetic coil; the provision of a second coil has the advantageous effect of doubling the magnetic field but it is not essential.

A third embodiment of the invention is illustrated in Figure 8. A channel 54 of insulating material is of rectangular cross section and supports two electrodes 56, 58 insulated from the moderately conducting liquid 60 flowing along the channel and arranged opposite each other on the vertical channel walls. The electrodes extend above and below the liquid in the channel and, in the direction of flow, are short compared with the channel width; for example their length may be half the channel width. Below the channel is a square magnetic coil 62 connected to an a.c. source 64. The coil is placed symmetrically with respect to the electrodes 56, 58 and the length of each side is about four or five times the width of the channel 54, two sides being parallel to the channel walls. 15 20

The magnetic field produced by such a coil is illustrated in Figure 9. At the centre of the coil, in the region corresponding to the part of the channel 54 between the electrodes 56, 58, the magnetic field lines are straight and vertical. The virtual current corresponding to such an arrangement is illustrated in Figure 8; the current flow is horizontal between the electrodes 56 and 58 and current density is invariant in a vertical direction, but the direction of current flow is parallel to the x axis only between the centres of the electrodes; at the upstream and downstream edges, current flow first diverges, then converges. 25

In this arrangement, as in Figures 1 and 5, the interelectrode capacitance C is directly proportional to the height of the liquid in the channel, the flow signal U is proportional to the flowrate divided by the liquid height and, as before, the flowrate can be determined by, e.g. simultaneous measurement of U and C and by analogue multiplication of the two using the circuit shown in Figure 4. Also, as in the Figures 1 and 5 embodiments of the invention, the flowmeter reading is substantially independent of velocity distribution. 30 35

In all of the embodiments described, the surface of the liquid in the channel is horizontal and therefore the required condition for the flowmeter according to the invention is that the virtual current flow is also horizontal and therefore parallel to the liquid surface. The flowmeter may also be used when the channel or pipe is slightly tilted in the axial direction, the virtual current remaining parallel to the liquid surface. 40

#### Claims

1. A flowmeter for measuring the flowrate of a liquid of moderate electrical conductivity comprises a duct of uniform cross section along which the liquid flows and in which the liquid has a horizontal free surface; two electrodes arranged one on either side of a vertical plane along the direction of flow and extending at least to the top and to the bottom of the liquid; means for applying a magnetic field to the fluid in the duct, the magnetic field having at least a component in the vertical direction and being invariant in the horizontal direction perpendicular to the liquid flow and between the electrodes; and potential sensing means for sensing the electrical potential between the electrodes caused by flow of the fluid; the arrangement being such that a virtual current between the electrodes would be horizontal and have no vertical component. 45 50

2. A flowmeter according to Claim 1 arranged so that between the liquid and each side of the sensing means there is an electrical admittance per unit area of the duct wall which is proportional to the cosine of the angle in the vertical plane between the normal to the internal wall of the duct and the horizontal, in which the length of the electrodes in the direction of flow is at least twice the maximum width of the liquid free surface, and in which the magnetic field is relatively narrow in the direction of flow, whereby a horizontal and one-dimensional virtual current would flow perpendicular to the liquid flow. 55

3. A flowmeter according to Claim 1 arranged so that between the liquid and each side of the sensing means there is an electrical admittance per unit area of the duct wall proportional to the normal component of any horizontal and two-dimensional virtual current field which is generally transverse to the liquid flow and relatively short in the axial direction, and the magnetic field is uniform over a length of the duct which is at least twice the maximum width of the liquid free surface, whereby a horizontal and two-dimensional virtual current would flow generally transverse to the liquid flow. 60

4. A flowmeter according to Claim 2 or Claim 3 in which the two electrodes are continuous

electrodes in contact with the outer wall of the liquid-containing duct, the duct being formed of a thin electrically resistive material of such thickness at any point that the electrical admittance per unit area is in the required relationship.

5. A flowmeter according to Claim 2 or Claim 3 in which the two electrodes each comprise a spaced array of electrodes all in contact with the inner insulating wall of the liquid-containing duct and each connected to the sensing means through an electrical resistance or impedance such that the electrical admittance divided by the area associated with each electrode in the array is in the required relationship. 5
6. A flowmeter according to Claim 3 in which the sidewalls of the channel are vertical and the electrodes are continuous electrodes insulated from the liquid. 10
7. A flowmeter according to any preceding claim further comprising admittance measuring means for measuring the electrical admittance between said two electrodes.
8. A flowmeter according to any one of Claims 1 to 6 further comprising a shorting resistor connected between said two electrodes, and voltage sensing means for sensing the voltage generated across the shorting resistor by flow of the liquid, said voltage being proportional to the flowrate of the liquid. 15
9. A method of measuring the flowrate of a liquid of moderate electrical conductivity comprising causing the liquid to flow along a duct of uniform cross section and in which the liquid has a horizontal free surface; applying to the fluid in the duct a magnetic field which has at least a component in the vertical direction and which is invariant in the horizontal direction perpendicular to the liquid flow; and sensing any electrical potential generated between the electrodes arranged on either side of a vertical plane along the direction of flow and extending at least to the top and to the bottom of the liquid, the arrangement being such that a virtual current between the two electrodes would be horizontal and have no vertical component. 20
10. A flowmeter for measuring the flowrate of a liquid of moderate electrical conductivity substantially as hereinbefore described with reference either to Figures 1 and 4 or to Figures 4 and 5 or to Figures 4 and 7 or to Figures 4 and 8 of the accompanying drawings. 25